

A Simple Maneuver Indicator from Target's Range-Doppler Image

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Abstract—Tracking maneuvering targets presents a great challenge to airborne surveillance radar signal processing and sensor systems management systems. Smears caused by an uncompensated maneuver (either translational or rotational) affect target identification (ID) with distorted target images. An unexpected maneuver introduces large position estimation errors to a tracker and in the worst case loss of track. On the other hand, a sensor manager relies upon an expected performance of a tracker to schedule its resources so as to maintain target ID/tracker performance. To aid a sensor management cost function, we present a simple target maneuver indicator (TMI) specifically for the operational condition of target maneuverability. It relates the slope of a target's range-Doppler image to the underlying turn rate, if the target undergoes a maneuver. As an intermediate product of the range profile formation process, this approach provides an easy and quick indication of target maneuverability and, under favorable conditions, an estimate of such a maneuver (e.g., the turn rate), which can be incorporated into the tracking algorithm of the tracker..

Keywords: Maneuver Estimation, Range-Doppler Imaging, Image Slope, Turn Radius, Turn Rate

1. Introduction

In a large area surveillance application, the revisit time may last as long as 10 seconds. The actual scan rate is not uniform as an advanced radar is often scheduled to operate in different modes during a scan with increased dwelling in certain directions for complex waveforms and sophisticated processing. In addition to ground moving target indicator (GMTI), a radar may be called upon to perform target identification (ID) or fingerprinting in the synthetic aperture radar (SAR) mode for stationary targets and in the inverse SAR (ISAR) or high range resolution (HRR) mode for moving targets.

With its two-dimensional (2D) details, SAR has been successfully applied to stationary target identification. However, the image quality is severely affected by target maneuvers (translational and rotational). A considerable amount of research is being devoted to

motion compensation to focus an image and to alleviate other distorting effects [10, 5]. On the other hand, one-dimensional (1D) HRR radar becomes attractive not only because it is less affected by target motion but also because it requires less dwell time and simpler processing [11, 6].

During a revisit period of 10 seconds, a ground vehicle can slow down, make a turn, and then speed away. It can even reverse its direction (making a U-turn). A conventional tracker based on a constant velocity model using position measurements can develop large errors prior to catching up with the target's maneuver and in the worst case losing track completely. It is therefore desired to extract as much information as possible especially about potential and ongoing maneuver from each glimpse of target when available.

For this purpose, we present a simple *maneuver indicator*, see Eq. (22) or (24), in this paper that can be derived from a target's range-Doppler image, an intermediate product of the HRR range profile forming process. It is well known that 1D HRR signatures are subject to high variability due to scintillation effects (speckles). That is, multiple scatterers falling in a single range bin interact either constructively or destructively when the aspect angle is changed slightly. Popular solutions to this problem include extracting target features from 2D raw HRR data and averaging them into a single averaged range profile [12]. By "2D raw HRR data," we mean the lining up of all of the 1D reflected pulses received by an HRR radar during one dwell period [6]. One axis of the 2D raw HRR data is the range while the other axis is the order of the reflected pulse in the sequence of radar returns.

When the phase history of individual range bins across the dwell time is analyzed in the frequency domain, it results in a range-Doppler image of the target. For a target undergoing constant motion relative to the sensor, a vertical line appears in the range-Doppler image. When the target undertakes a maneuver, the differential Doppler experienced by the scatterers on target tilts the image. Clearly, any significant deviation from the ideal verticalness provides an indication of an ongoing maneuver, which

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we propose to use in this paper to alert subsequent signal processing and tracking algorithms to improve the overall performance.

This range-Doppler imaging of a target is similar to the ISAR operation in the sense that a target is resolved in the cross-range via differential Doppler. However, its use for maneuver detection is much simpler than ISAR imaging. The latter typically requires longer dwell time and more sophisticated processing for motion compensation and other image-forming operations. In a sense, it is a tradeoff between obtaining quick maneuver information as a by-product of HRR for target ID vs. performing ISAR with lengthy motion compensation.

The rest of the paper is organized as follows. In Section 2, the relationship between a target's turn rate and the slope of its range-Doppler image is derived as the basis for quick maneuver detection. In Section 3, the simulation tools that are used to generate target RF signatures are described. In Section 4, simulation results are presented to show the operation and performance of the simple maneuver indicator. Finally in Section 5, conclusions are drawn together with future work.

2. Maneuver Information from Range-Doppler Images

In this section, we show how to estimate a target's turn rate from the slope and slope rate of the target's range-Doppler image. If the target's state (position and velocity) is available, say, from a tracker prediction, the turn rate as well as the turn radius can be estimated from the slope alone. A target's size information is also useful when it is related to the target dimension in the range-Doppler image.

A target's range-Doppler image is generated from the returns of a train of pulses over a short coherent integration interval (CPI). A radar can transmit a pulsed chirp waveform with a linearly increasing frequency (a linear FM pulse) or a stepped frequency

waveform, which is a continuous wave (CW) with its frequency increased in step to cover a desired bandwidth. The centroid of a target's range-Doppler image provides an average measurement of the target's range and range rate (Doppler frequency shift).

A straight-moving target will produce energy concentrated in a small number of Doppler bins. When a target makes a turn, its energy is spread over an increased number of range and Doppler bins. For a target moving along a circular path, its heading change causes a difference in the velocity between the target front and target rear. The skin-line thus appears to be slanted in the range-Doppler image as opposed to completely vertical. The slope of the skin-line therefore can be used to detect a turning maneuver. Along with some information about the target's initial heading, it can further indicate the target turning direction. In addition, the turn rate and the turn radius can be obtained from the slope together with an estimate of the target's velocity vector from a tracker or the slope rate estimated from the same range-Doppler images.

A simple encounter geometry is shown in Fig. 1 in the ground plane, which is related to the slant range plane by $\cos(\varphi)$ where φ is the depression angle or elevation. Consider a target that is moving at a constant velocity (at the centroid) v_t and making an angle θ with the projected line of sight (LOS) on the ground plane (called the target centric azimuth or azimuth for short).

The target is shown as a widthless stick of length L in Fig. 1. Its corresponding range-Doppler image is shown in Fig. 2. A right-hand coordinate system is attached to the target where the x -axis is pointing out of the nose, the y -axis to the left, and the z -axis to the top. The positive azimuth is to the left and the positive turn is also to the left.

For the range-Doppler image shown in Fig. 2, the target's image length (Δr) and the centroid Doppler frequency f_d (i.e., the range rate \dot{r}) are given by:

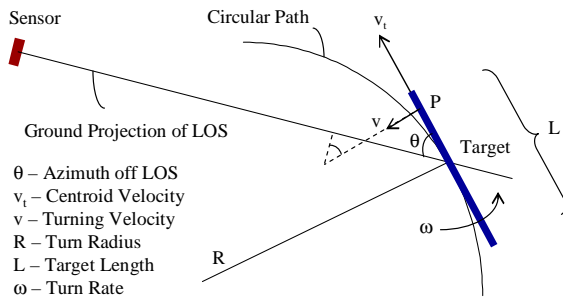


Fig. 1 – Encounter Geometry

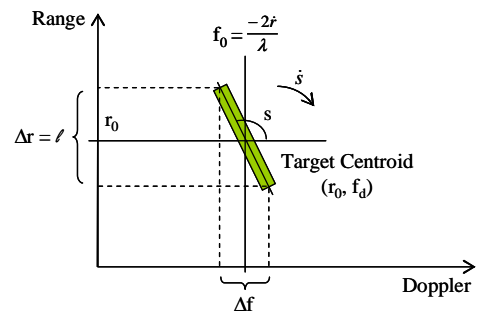


Fig. 2 – Range-Doppler Image

$$\ell = L \cos(\theta) \cos(\varphi) \quad (1)$$

$$\dot{r} = v_t \cos(\theta) \cos(\varphi) \quad (2)$$

where L is the target longitudinal length.

It is reasonable to assume that the elevation angle φ changes little during the time period of analysis. From (1) and (2), we can derive the target velocity if we know its length L and its image size ℓ :

$$v_t = \frac{L}{\ell} \dot{r} \quad (3)$$

If we can measure the image size ℓ and know its actual length L , then together with an approximate value for φ , we can obtain an estimate of the azimuth (with a sign ambiguity) as:

$$|\theta| = \cos^{-1}\left(\frac{\ell}{L \cos(\varphi)}\right) \quad (4)$$

The target image length ℓ may be obtained by counting the number of pixels (range resolution bins) in the range-Doppler images or from the range profile matching with properly scaled templates.

As shown in Fig. 2, for a target turning at a constant speed v_t , the velocity of the target projected onto the line-of-sight produces a Doppler shift of the target:

$$f_d = -\frac{2}{\lambda} \dot{r} = -\frac{2}{\lambda} v_t \cos(\theta) \cos(\varphi) \quad (5)$$

where λ is the wavelength of the center frequency of the radar.

For a target moving around a circular path, we can decompose the motion of the target into two components. The first is the movement of the center of the target around the circular path and the second is the "spinning" of the target about its center. It is this second component that causes the skin line to appear slanted in the range-Doppler image, because the front of the target is moving at a different velocity than the back of the target. The slope, denoted by s , of the skin line can be written as:

$$s = \frac{\text{Range Extent}}{\text{Doppler Spread}} = \frac{\Delta r}{\Delta f} \quad (6)$$

The sign of the slope indicates whether the target is turning toward or away from the sensor. Assuming that the range-Doppler image is plotted with near ranges at the bottom of the figure, a negative slope indicates that the target is turning toward the sensor.

Consider a point P located on the target 1 m from its center. Projected onto the line-of-sight of the radar, this one meter distance appears in the range as:

$$\Delta r_p = \cos(\theta) \cos(\varphi) \quad (7)$$

This point will also have a Doppler shift relative to the center of the target of:

$$\Delta f_p = -\frac{2}{\lambda} v \sin(\theta) \cos(\varphi) \quad (8)$$

where v is the speed of that point relative to the center of the target.

In other words, v is the rate at which that point is spinning around the target centroid. If the target were to make one full revolution around the circle of radius R , the point P would also make one full revolution around the target centroid in the same amount of time. We can write the time that it takes for the target to make one full revolution as:

$$t = \frac{2\pi R}{v_t} \quad (9)$$

We can also write the amount of time the point P takes to make one full revolution as:

$$t = \frac{2\pi}{v} \quad (10)$$

Setting (9) equal to (10) and solving for v gives:

$$v = \frac{v_t}{R} \quad (11)$$

which is also the angular rate of the turn, defined as ω for this linear velocity at unit distance:

$$\omega = \frac{v_t}{R} \quad (12)$$

Bringing (7) and (8) into (6) yields:

$$s = \frac{\cos(\theta) \cos(\varphi)}{-\frac{2}{\lambda} v \sin(\theta) \cos(\varphi)} = \frac{-\lambda R}{2v_t \tan(\theta)} = \frac{-\lambda}{2\omega \tan(\theta)} \quad (13)$$

The second equality is obtained using (11); and the last equality makes use of (12).

Solving for R from (13), we get:

$$R = \frac{-2v_t s \tan(\theta)}{\lambda} \quad (14)$$

Solving for ω from (13), we get:

$$\omega = \frac{-\lambda}{2s \tan(\theta)} \quad (15)$$

By estimating the slope of the skin line, we can determine the turning rate from (15) as well as the turning radius from (14) given an estimate of the target state. Assume that the sensor's position \underline{x}_s and velocity \underline{v}_s are known and the predicted target position and velocity at the time of HRR measurement taking are $\bar{\underline{x}}_t$ and $\bar{\underline{v}}_t$, respectively. The azimuth off LOS is given by:

$$\bar{\theta} = \cos^{-1}\left(\frac{(\underline{x}_s - \bar{\underline{x}}_t, \underline{v}_s - \bar{\underline{v}}_t)}{\|\underline{x}_s - \bar{\underline{x}}_t\| \|\underline{v}_s - \bar{\underline{v}}_t\|}\right) \quad (16)$$

The predicted radius of turn is

$$\bar{R} = \frac{-2\bar{v}_r \hat{s} \tan(\bar{\theta})}{\lambda} \quad (17)$$

And the predicted angular rate is

$$\bar{\omega} = \frac{-\lambda}{2\hat{s} \tan(\bar{\theta})} = \frac{-\lambda \hat{\gamma}}{2 \tan(\bar{\theta})} \quad (18)$$

where \hat{s} is the slope measured from a target's range-Doppler image and $\hat{\gamma}=1/\hat{s}$ is the co-slope, which is useful when the target image is close to vertical.

Under the assumption that R and v_r are constant over a short period of time, taking time-derivative of (13) gives

$$\dot{s} = -\frac{\lambda}{2 \sin^2(\theta)} < 0 \quad (19)$$

which is derived using the following relationship between the azimuth and the angular rate according to the sign conventions introduced for Fig. 1:

$$\theta = \theta_0 - \omega t, \quad \theta = \theta_0 \text{ when } t = 0 \quad (20)$$

From (20), we have the angular rate equation as:

$$\dot{\theta} = -\omega \quad (21)$$

(19) shows an interesting property of a target's range-Doppler image. With reference to the axes of range (near at the bottom) and Doppler (positive to the right) as defined in Fig. 2, the slanted line always rotates clockwise under turning maneuvers.

When the slope rate is estimated from a sequence of range-Doppler images, the turn rate can be determined directly as

$$\omega = \text{sign}(\theta) \frac{-\lambda}{2s} \sqrt{\frac{-2\dot{s}}{\lambda} - 1} \quad (22a)$$

$$|\omega| = \frac{-\lambda}{2s} \sqrt{\frac{-2\dot{s}}{\lambda} - 1} \quad (22b)$$

where $\text{sign}(\cdot)$ is the sign function of the argument. If $\text{sign}(\cdot)$ is not known, the sign of the angular rate cannot be determined. The sign ambiguity is readily solved for a tracker as it can be estimated as in (16).

Although the slope definition in (6) makes use of the target image extent along the range and Doppler dimensions, the actual calculation of the slope resorts to such techniques as curve-fitting. When $\theta = 0^\circ$ (in a head-on or tail chase encounter), the line is vertical and the slope is not well defined (infinite). This poses a numerically difficult. To avoid this problem when θ is near zero, a co-slope defined as $\gamma = 1/s$ may be used instead (simply switch the order of the x and y coordinates in the computation).

Still in this case with $\theta = 0^\circ$, even there is a maneuver, the target image remains vertical because Doppler frequencies developed in both sides of a target from the front to the rear, though of different signs,

have the same value as shown in Fig. 3. However, the Doppler spread may be significant as given by:

$$\Delta f = \frac{2}{\lambda} W \omega \cos(\varphi) \quad (23)$$

where W is the width of the target. This spread as compared to the Doppler resolution can be used as an indicator for maneuver. If the target width W and the depression angle j are known, the turn rate can be estimated as:

$$\omega = \frac{\lambda \Delta f}{2W \cos(\varphi)} \quad (24)$$

When $\theta = 90^\circ$, the slope is difficult to estimate because the range extent is small and the range rate gets into the clutter ridge (i.e., below the minimum detectable velocity or MDV). Mathematically, $\tan(\theta)$ goes to infinite at this point and the slope is zero. As a singularity point, it is a blind spot to any Doppler radar. However, if the target makes a significant turn, the Doppler spread as given by (24) may reveal the target out of the clutter ridge (i.e., above the minimum detectable velocity or MDV).

In Fig. 4, the trajectory traced out by the extreme scatterers of a target (assumed to be visible) is compared to the geometrical circle in the same range-Doppler plane. Rearranged from (1), the geometrical circle has the following polar representation (centered at the centroid Doppler frequency):

$$\rho = \rho_0 \cos(\theta), \quad \rho_0 = \frac{1}{2} L \cos(\varphi) \text{ when } \theta = 0 \quad (25)$$

Also shown in Fig. 4 are the signs for the azimuth θ and angular rate ω . The target image trace differs from the geometrical circle by a unit conversion factor which is proportional to the angular rate as can be seen from (13).

Based on the above analysis, a practical procedure for maneuver detection and estimation may include the following steps:

- Test for the verticalness of a target range-Doppler image.
- If it is near vertical, estimate the Doppler spread against frequency resolution. If available, the side information about the azimuth angle off LOS can be used to assist this step particular for $\theta = 0^\circ$ or 90° . If not significant, there is no maneuver. If significant, there is a maneuver.
- Convert the Doppler spread into maneuver information (turn rate, turn radius) given the target's dimension and predicted position and velocity.
- If it is not vertical, estimate the slope of a target range-Doppler image.

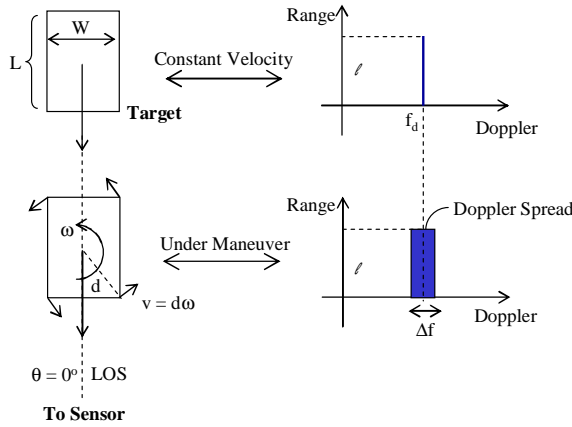


Fig. 3 – Encounter Geometry and Range-Doppler Images for $\theta = 0^\circ$

- Convert the slope estimate into maneuver information (turn rate, turn radius) given the target's predicted position and velocity.
- Alternatively, estimate the slope rate of a target range-Doppler image from a sequence of such images.
- Convert the slope and slope rate estimates into maneuver information (turn rate, turn radius).

3. Software Tools and Simulation Environment

To study the effects of target maneuvers on range-Doppler data in general and to validate the maneuver estimation algorithm as described in Section 2 in particular, it is necessary to develop a simulation environment with software tools that are easy to use and capable of producing data with realistic features. One simulation is developed in MATLAB for this study as shown in Fig. 5. It is based on the Simulation Tool for Advanced Radar Systems (STARS), developed by ATK Mission Research (Dayton, OH) [9]. STARS utilizes a stationary target's phase center data to simulate realistic moving target data. As such, it is a valuable tool in studying maneuver detection.

A trajectory generator is used to create a radar-target encounter scenario, from which the target-centric azimuth is calculated. The target-centric azimuth, together with the radar depression angle, is fed to a radar signature generator to produce the scatterer phase center data, that is, the location and complex radar cross section (RCS) of each of the scattering centers composing the target. Based on the scatterer phase center data, STARS implements a unique stepped-frequency high range resolution radar, producing the target phase history response, to which noise and clutter data may be computed by STARS in some cases and then coherently added. A moving target's HRR range profile can be extracted from the target phase history data for target ID and fingerprinting as shown

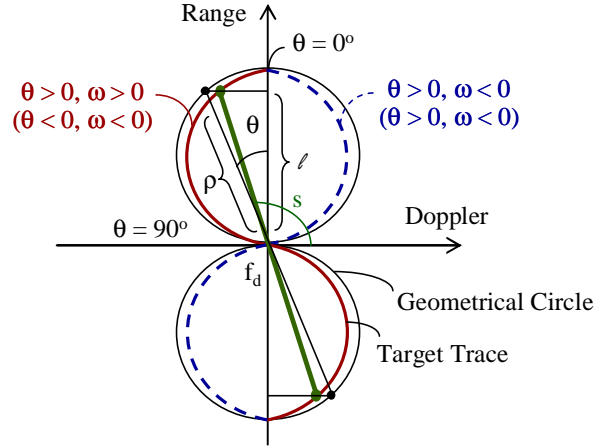


Fig. 4 – Range-Doppler Trajectory in the Image Plane

in Fig. 5. On the other hand, the target phase history data are used to form a range-Doppler image of the target from which the slope is estimated as a simple maneuver indicator.

STARS can work with scatterer phase center data produced by any radar signature generator and even with an ideal grid model. The two particular radar signature generators identified in Fig. 5 are Xpatch and SigPred. The latter is further described in Fig. 6. SigPred was developed by General Dynamics Advanced Information Systems (Ann Arbor, MI) under the Air Force program Feature-Aided Tracking of Stop-move Objects (FATSO) [8].

As shown in Fig. 6, the software package Radar Reflector Extractor (RAREX) converts CAD models into intermediate representations called reflector-primitive (RP) models such as flat plates, dihedrals, trihedrals, elliptic cylinders, elliptic cones, top hats, and shallow cavities. These simple geometry-shaped objects have known analytical solutions for their electromagnetic scattering behavior. RAREX may take minutes to hours to run, typically prepared off-line but once done it can be put into a database for future use.

Target signatures are generated from the reflector-primitive models by the Radar Signature Predictor (RSP) or SigPred. It first produces a set of reflectivity phase centers at the desired aspect, frequency, polarization, and resolution in terms of amplitude, phase, and location. These phase centers are then projected from the 3D space onto the radar collection plane. The scenario geometries supported by the software include vehicle viewing over 360° in azimuth and 5° to 45° in elevation, radar center frequencies in S band through K band, resolutions of one inch and above, and all polarization combinations.

The collection geometry including the target pose (*i.e.*, the target-centric azimuth and elevation of the view direction) is specified by the user through a GUI

when SigPred is run standalone or via an ASCII data file or as command line arguments when it interacts with another program such as MATLAB. In addition to an HRR range profile, SigPred also returns the location and complex RCS of each of the scattering centers composing the target. Since SigPred only produces the stationary target data, STARS is used to simulate moving target data from stationary target data, as illustrated in Fig. 5.

4 – Simulation Results and Analysis

To estimate the slope of a target's range-Doppler image, there are at least two types of slope estimation methods. One is simple shape-based using a target image mask whereas the other also takes into account the strength of a return (an image-weighted solution). The latter includes the eigenvalue decomposition technique [9]. It consists of forming a matrix ($N \times 2$) containing the two coordinates (range bin vs. frequency bin) of N on-target pixels relative to the center of mass, computing the weighted covariance matrix (2×2) of the coordinate matrix, and performing an eigenvalue decomposition of the covariance matrix. The resulting eigenvector along the longest dimension of the target provides an estimate of the slope.

For a shape-based technique, a target image is segmented out from the scene and represented by a simple mask, indicating which pixels are on-target. This is done using CFAR followed by a sequence of binary morphology. Several methods to estimate the target slope from its range-Doppler images have been developed [13, 14]. This includes the classic least squares (LS) method, the total least squares (TLS) method [7], the least absolute deviations (LAD) method [4], the width-based method, and the projection method [13].

Due to short-term stability of target scatterer distribution with respect to time and aspect angle, more sophisticated image processing techniques may be employed to improve the estimation accuracy of slope and slope rate. One possible technique is to align successive range-Doppler images via a rotation and scale-invariant transform (*e.g.*, the Fourier-Mellin transform) [1], thereby obtaining the incremental rotation as the slope rate..

The accuracy of maneuver estimation depends upon the accuracy with which the slope and the slope rate be estimated from a target's range-Doppler image. In addition to signal to noise and clutter ratio, the Doppler resolution plays a critical role in this estimation process. Since the Doppler resolution is inversely proportional to the coherent processing interval (CPI), a longer CPI yields a better Doppler resolution. However, during a long CPI (*e.g.*, one second), the

aspect of a target may change so much that smearing in Doppler occurs. As a result, the target energy no longer looks like a straight, sloped line, but has some curvature.

One technique is to split the long CPI into a number of (possibly overlapping) sub-apertures. These sub-apertures can be imaged individually (zero-padded first to keep the Doppler resolution same as the original one) to produce a sequence of slope estimates at varying target aspects. This also allows the slope rate to be estimated from the sequence of slopes in an approximate manner, assuming that the turn rate is constant throughout the CPI.

For a sequence of non-overlapping sub-apertures (*i.e.*, $\frac{1}{4}$ second), Table 1 lists the maneuver estimation results. There are 4 rows in the table, each representing a short CPI of $\frac{1}{4}$ seconds. For each row, there are 9 columns. The first column is the index for a CPI. The second column lists the target centric azimuth at the start of each CPI. The third column lists the true slope calculated from (13). The fourth column lists the slope estimated from the target's range-Doppler image using the least square method. The fifth column lists the true slope rate calculated from (19). The sixth column lists the estimated slope rate calculated from two consecutive slope estimates. For this reason, the first short CPI does not have a slope rate estimate. The seventh column lists the estimated turn rate using the slope and slope rate according to (22). The eighth column lists the estimated turn rate from the estimated slope, the target azimuth and velocity according to (18). Finally, the ninth column lists the estimated turn radius using the slope estimate, the target azimuth and velocity according to (17).

The estimated slopes in Column 4 are the average values whereas those true values in Column 3 are pertaining to a particular time instant. The estimated values lag behind the true ones by 11%. Again, the true slope rates in Column 5 are pertaining to a particular time instant whereas the estimated slope rates in Column 6 are estimated as time interval-scaled difference. In this sense, the estimate value corresponds better to the starting time of each CPI. This can be seen by comparing the slope rate estimation errors. The average error per row is 34% while the average error compared to the true values in the previous two rows is 14%, a better than half improvement. In Column 7, the estimated turn rates using the slope rates are off the true rates by 12.53% while the estimates using the slope in Column 8 are off by 13.24%. The turn radius estimation error is 11.73% in Column 9.

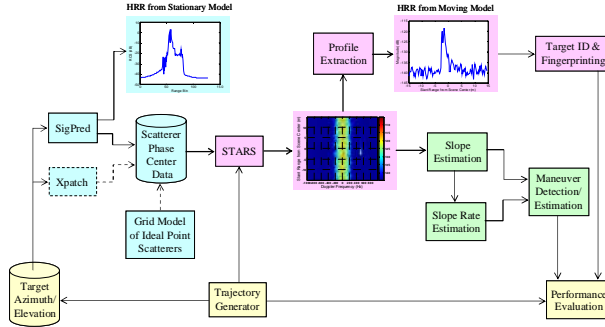


Fig. 5 – Use of STARS for Target ID & Maneuver Detection

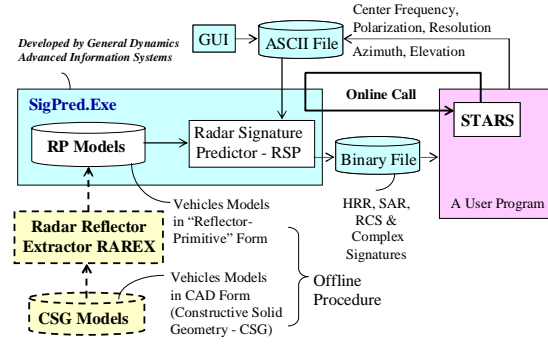


Fig. 6 – Target Radar Signature Generation with SigPred

Table 1 – Maneuver Estimation Results for Simple Target Model ($\omega = 34.4$ deg/sec, $R = 10$ m)

Sub CPI	Center Azimuth	True Slope	Estimated Slope	True Slope Rate	Estimated Slope Rate	Estimated Turn Rate 1	Estimated Turn Rate 2	Estimated Turn Radius
1	40.8	-0.029	-0.026	-0.035	--	--	38.925	8.832
2	31.9	-0.040	-0.036	-0.054	-0.040	31.123	38.918	8.833
3	22.9	-0.059	-0.051	-0.099	-0.062	29.905	39.733	8.652
4	14	-0.100	-0.090	-0.256	-0.156	29.252	38.239	8.990

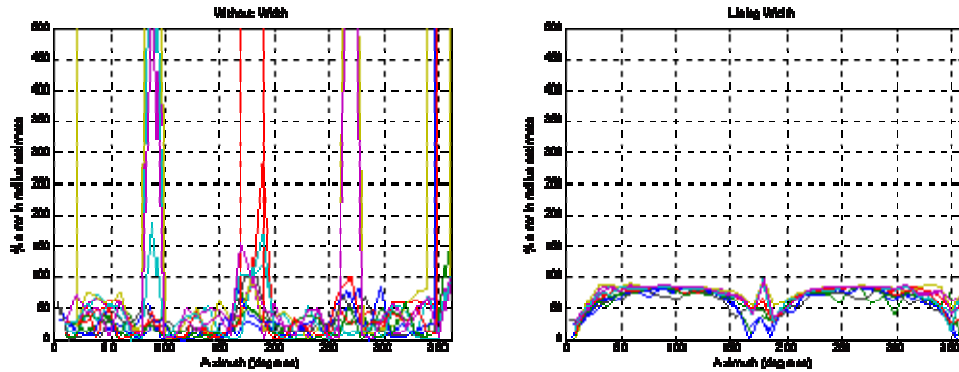


Fig.7 – Radius Error Estimate vs. Azimuth
(Left: Line Projection Methods; Right: Width-Based Method)

For a more realistic target model, namely, a SigPred Vehicle Transport, turning maneuvers with turn radius of 10, 20, 40, 60, 80, and 100 m for tangential speed of 6 and 10 m/s, respectively, are simulated. The radar center frequency is 10 GHz with a PRF of 2000 kHz. For each target and each turning radius, a range-Doppler map is generated every 10 degrees in azimuth, from which the slope is estimated. The accuracy is estimated in terms of the turn radius error percentage for a variety of turning rates. This serves as an indication of the slope errors and factors in the amplification effect of azimuth. The results are shown in Fig. 7. In these plots, each curve represents the result for a given turn radius. As expected, all curves spike at broadside angles (closer to 90 or 270 degrees, below

MDV in clutter ridge), and to a lesser degree, at end-on angles (closer to 0 or 180 degrees, an infinite slope).

When the target is very near the cardinal angles, the slope of the target changes very rapidly. A small error in the mask can cause large errors in the slope estimate. In such cases, it is reasonable to consider the alternative method of (24) that estimates the turning rate using the width of the target, rather than the slope. This method appears to perform better when the target is near a 0 degree or 180 degree azimuth. Fig. 7 compares the projection slope estimation method to the method utilizing the width of the target. Although showing larger errors, the width-based method clips the maximum errors experienced by the projection method. Clearly, one way to improve the overall estimation is to

let the two methods operate in different azimuth intervals and then piece up (fuse) the final results.

In the current simulation, we only considered the yaw motion of the target (about the z-axis for heading change), which is the predominant maneuver of ground targets. However, a target is likely to be subject to simultaneous roll, pitch, and yaw motions particularly for a ground vehicle on an uneven road surface. Such motions are known to create smears in ISAR images [2], which require sophisticated motion compensation algorithms to clear up. Nevertheless, such smearing exhibits some degree of symmetry along the Doppler axis, which is less a problem for slope estimation than for visual recognition.

The maneuver estimate and the estimation error statistics are important information that a target tracker can incorporate into its tracking algorithm so as to improve the overall performance. In a similar manner, better information about target tracks and particularly ongoing maneuvers can assist a sensor manager to allocate its limited resources and schedule timely activities more efficiently.

5 – Conclusions

In this paper, we presented a simple method to detect a target maneuver from its range-Doppler image when the skin line tilted away from verticalness. We also derived the relationship between the turn rate of a maneuvering target and the slope and slope rate of its range-Doppler image. Simple methods were described for slope and slope rate estimation, leading to turn rate estimates. Synthetic target range-Doppler images were generated using SigPred and STARS and used to demonstrate the operation and performance of the simple maneuver indicator for various encounter scenarios.

One way to improve the overall estimation performance is to operate different methods in different azimuth intervals and then piece up (fuse) the final results. Another direction of future work will develop more sophisticated image processing techniques. Such effects as limited resolutions, particularly in the Doppler axis, and noise and clutter as well as 3D motion also needs to be assessed.

Not all targets will be caught undertaking a maneuver. Once captured in a scan, the maneuver information is time-critical and its estimate should be used by the tracker to the full extent possible. Efforts are under way to incorporate the target maneuver indicator into a target tracker for simulation and evaluation (*e.g.*, as in [3]), which will be reported in future papers.

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